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Worldwide application of aquifer thermal energy storage – A review

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ABSTRACT

To meet the global climate change mitigation targets, more attention has to be paid to the decarbonization of the heating and cooling sector. Aquifer Thermal Energy Storage (ATES) is considered to bridge the gap between periods of highest energy demand and highest energy supply. The objective of this study therefore is to review the global application status of ATES underpinned by operational statistics from existing projects. ATES is particularly suited to provide heating and cooling for large-scale applications such as public and commercial buildings, district heating, or industrial purposes. Compared to conventional technologies, ATES systems achieve energy savings between 40% and 70% and CO_2 savings of up to several thousand tons per year. Capital costs decline with increasing installed capacity, averaging 0.2 Mio. € for small systems and 2 Mio. € for large applications. The typical payback time is 2–10 years. Worldwide, there are currently more than 2800 ATES systems in operation, abstracting more than 2.5 TWh of heating and cooling per year. 99% are low-temperature systems (LT-ATES) with storage temperatures of < 25 °C. 85% of all systems are located in the Netherlands, and a further 10% are found in Sweden, Denmark, and Belgium. However, there is an increasing interest in ATES technology in several countries such as Great Britain, Germany, Japan, Turkey, and China. The great discrepancy in global ATES development is attributed to several market barriers that impede market penetration. Such barriers are of socio-economic and legislative nature.

1. Introduction

The global community has to face a paradigm shift towards a sustainable energy supply to keep the increase in the global average temperature to within 2 °C above pre-industrial levels. While the share of renewables in the power generation sector increases continuously, less attention is paid to the decarbonization of the heating and cooling sector. In 2015, heating and cooling accounted for half of the total world final energy consumption, with three-quarters produced from fossil fuels. The share of modern renewable technologies is currently estimated at only 8% [1]. At the same time, global energy consumption for heating and cooling is expected to further increase with rising prosperity, population growth, and climate change. According to IPCC (Intergovernmental Panel on Climate Change), power consumption for air conditioning alone is expected to rise 33-fold by 2100 [2]. To achieve the climate change mitigation targets, increasing attention has to be paid to the decarbonization of the thermal energy sector.

The key challenge of increasing the share of renewables in the heating and cooling sector is attributed to the seasonal offset between thermal energy demand and supply. To tackle this seasonal mismatch, the idea of Thermal Energy Storage (TES) has attracted increasing attention [3]. The selection of an appropriate storage method depends on several factors such as storage capacity, storage duration, and supply and demand temperature [4,5]. Underground Thermal Energy Storage (UTES) is a sensible TES method, characterized by high storage efficiencies [6,7] and high storage capacities and is therefore the preferred choice for long-term TES. The most popular sensible seasonal UTES techniques are illustrated in Fig. 1. UTES can be further subdivided into open-loop or closed-loop systems. In open-loop systems, also referred to as Aquifer Thermal Energy Storage (ATES), sensible heat and cold is temporarily stored in the subsurface through injection and withdrawal of groundwater [8–10].

Closed-loop systems are more or less independent of the permeability of the subsurface and are called Borehole Thermal Energy Storage (BTES). In Tank Thermal Energy Storage (TTES), Pit Thermal Energy Storage (PTES), and Cavern Thermal Energy Storage (CTES),

Abbreviations: AR, Artificial Recharge; ATES, Aquifer Thermal Energy Storage; BTES, Borehole Thermal Energy Storage; CCS, Carbon Capture and Storage; CTES, Cavern Thermal Energy Storage; ECES, Energy Conservation through Energy Storage; GHG, Greenhouse Gas; GSHP, Ground Source Heat Pump; HT, High Temperature; HVAC, Heating, Ventilation, and Air Conditioning; IEA, International Energy Agency; IPCC, Intergovernmental Panel on Climate Change; LT, Low Temperature; PTES, Pit Thermal Energy Storage; TES, Thermal Energy Storage; TRL, Technical Readiness Level; TTES, Tank Thermal Energy Storage; UTES, Underground Thermal Energy Storage

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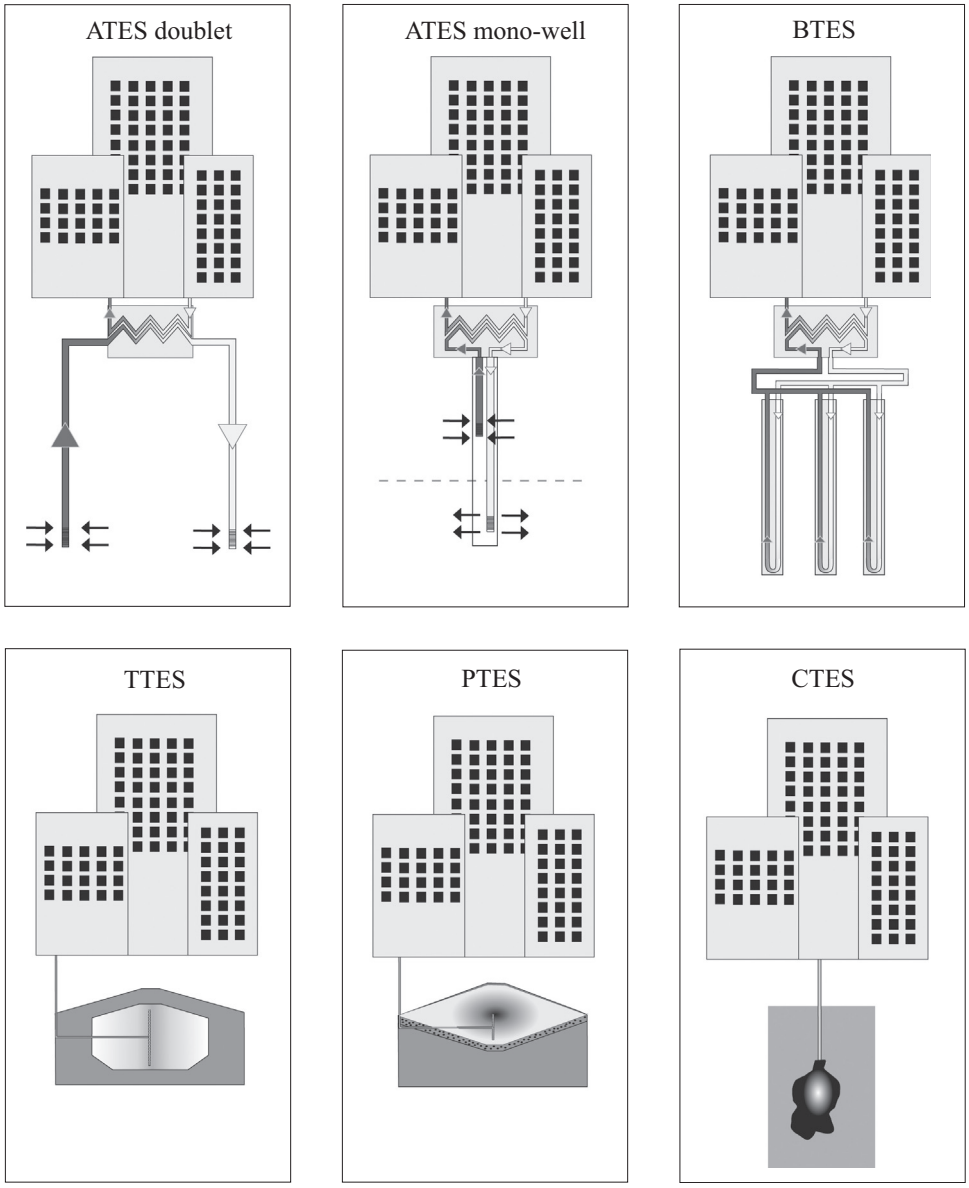

Fig. 1. Seasonal sensible UTES techniques. BTES, Borehole thermal energy storage; TTES, Tank thermal energy storage; PTES, Pit thermal energy storage; CTES, Cavern thermal energy storage.

Table 1
Comparison of seasonal Underground thermal energy storage (UTES) concepts (+ + + high; + + moderate; + low).

	PTES / TTES	ATES	BTES
Storage medium	Water; water/ gravel	Groundwater/ sediments	Groundwater/ sediments
Subsurface requirements	+	+ + +	+ +
Required pre-investigation	+	+ + +	+ +
Maximum storage capacity (kwh/m^3)	+ + +	+ +	+
Storage volumes	+	+ + +	+ +
Space requirement	+ + +	+	+
Investment costs	+ + +	+	+ +
Maintenance	+	+ + +	+
Environmental interaction	+	+ + +	+ +

heat and cold is stored in thermally stratified storage tanks, dug pits filled with gravel and water, or naturally occurring cavities, respectively. Table 1 compares these UTES techniques regarding technical and subsurface-related aspects.

Among different seasonal UTES concepts, ATES is characterized by the highest storage capacities and is therefore most suitable for large-scale applications [11]. However, ATES application requires the presence of an aquifer and suitable hydrogeological conditions such as a low groundwater flow, high permeabilities, and geochemical conditions that prevent clogging and corrosion of wells. Compared to standard open-loop geothermal systems, ATES systems require a more complex pre-investigation and are typically more sensitive to groundwater flow and aquifer heterogeneities. The seasonal storage of heat and cold, however, enables a more efficient operation.

The objective of this work is to review the historical development and the current global application status of ATES. Based on the reviewed literature, system designs, trends, and ideas developed over time are summarized with special attention on operational parameters of successfully implemented ATES systems. Since the literature lacks statistics on the number of implemented ATES systems, the review of

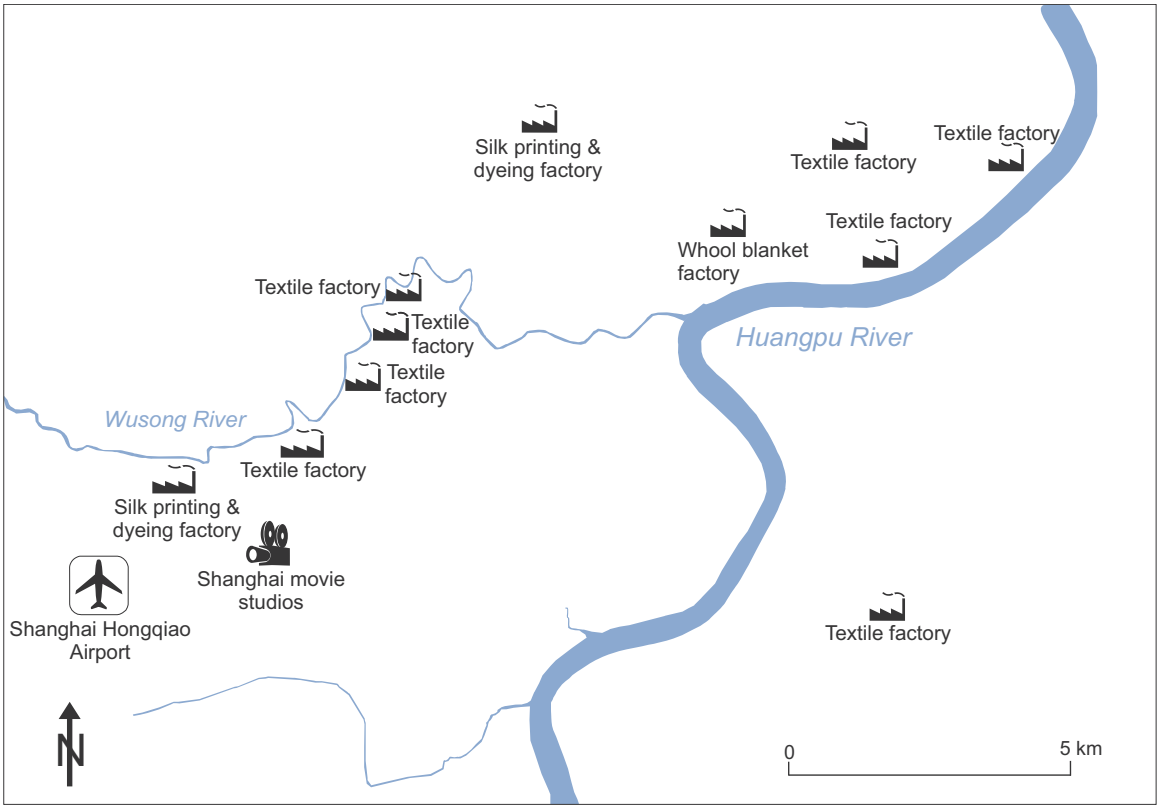

Fig. 2. Early ATES sites in Shanghai used for industrial cooling (modified based on [12]).

previous work is complemented by an analysis of the current ATES application status. Based on these country-by-country statistics, market barriers for entering a commercialization level are finally identified and discussed in order to stimulate future ATES research and projects.

2. Historical and technical development of ATES worldwide

2.1. A retrospective: from idea to market penetration

The idea of storing heat and cold in aquifers can be traced back to the mid-1960s [12–19]. To reduce subsidence as a consequence of long-term groundwater over-pumping, artificial recharge (AR) was successfully proposed in Shanghai in the early 1960s [20]. Soon, investigations indicated that the injected surface water preserved its temperature over several months. Subsequently, Shanghai's textile industry became aware of the great potential of AR for industrial cooling, and several factories started to actively store winter cold for summer cooling [19,21–23]. Given the high demand for industrial cooling, the number of ATES applications increased gradually in the following years. Fig. 2 illustrates early ATES applications for industrial cooling in Shanghai.

By 1984, more than 400 wells were used for both injection and extraction, storing a total of 1100 TJ of cooling energy in Shanghai annually [18]. Utilization of ATES peaked in the early 1980s, with more than 20 cities promoting ATES in China [14,15]. However, these projects were not sustainable. Clogging of wells or heat exchangers due to hydrochemical properties of the aquifer fluid and inappropriate well configuration forced many ATES systems to stop operating [24].

With the beginning of the oil crisis in the mid-1970s, the research into and development of energy storage were intensified, and the idea of storing thermal energy in aquifers started in North America and Europe [25,26]. Fig. 3 visualizes ATES development over time, highlighting important research projects as well as experimental and commercial ATES milestones.

Pioneering work was done by Kazmann [28], Rabbimov et al. [29], Meyer and Todd [30], and Sauty et al. [31,32], who carried out early theoretical and also field studies. Based on this theoretical framework, several field experiments were designed and conducted (Table 2). The first ATES experiment was performed by the University of Neuchâtel (Switzerland) in 1974 [17,33,34], followed by a three-stage experimental project at Auburn University (US) in 1976 [35–38,40]. Further countries such as France, Japan, Germany, or Canada started participating in ATES research with their own experimental field sites.

While Shanghai's industry applied ATES predominantly for industrial cooling, early research in ATES also focused on the storage of higher temperatures > 40 °C. As practical experience with the storage of high temperatures was rare, many early ATES sites faced considerable difficulties. The most frequent problems were related to:

- Scaling and clogging of wells and heat exchangers [37,43,59,64,90,92–99]
- Corrosion of wells [25,49,59,63,68,73,85,93,94,100]
- Buoyancy flow or thermal breakthrough [25,35,43,44,101–104]
- Unbalance between stored heat and cold [25,105]
- Swelling of clay minerals [59,90,96]

In 1978, the International Energy Agency (IEA) established the implementing agreement on Energy Conservation through Energy Storage (ECES) [106–109]. The target of ECES was to support research into and development of energy storage systems [110]. Periodic "Stock" conferences were established to share experiences with TES, starting in Versailles in 1981 [111]. Within this framework, great efforts were made to develop measures to prevent scaling and clogging [35,59,68,88,91,99,112–117], to overcome thermohydraulic-related problems such as thermal breakthrough, buoyancy flow, or unbalance between the stored heat and cold [31,36,44,74,104,118–136], and also to evaluate potential impacts of ATES on the environment [88,100,137–141]. The research showed that most problems can be avoided by careful pre-investigation and an appropriate operational

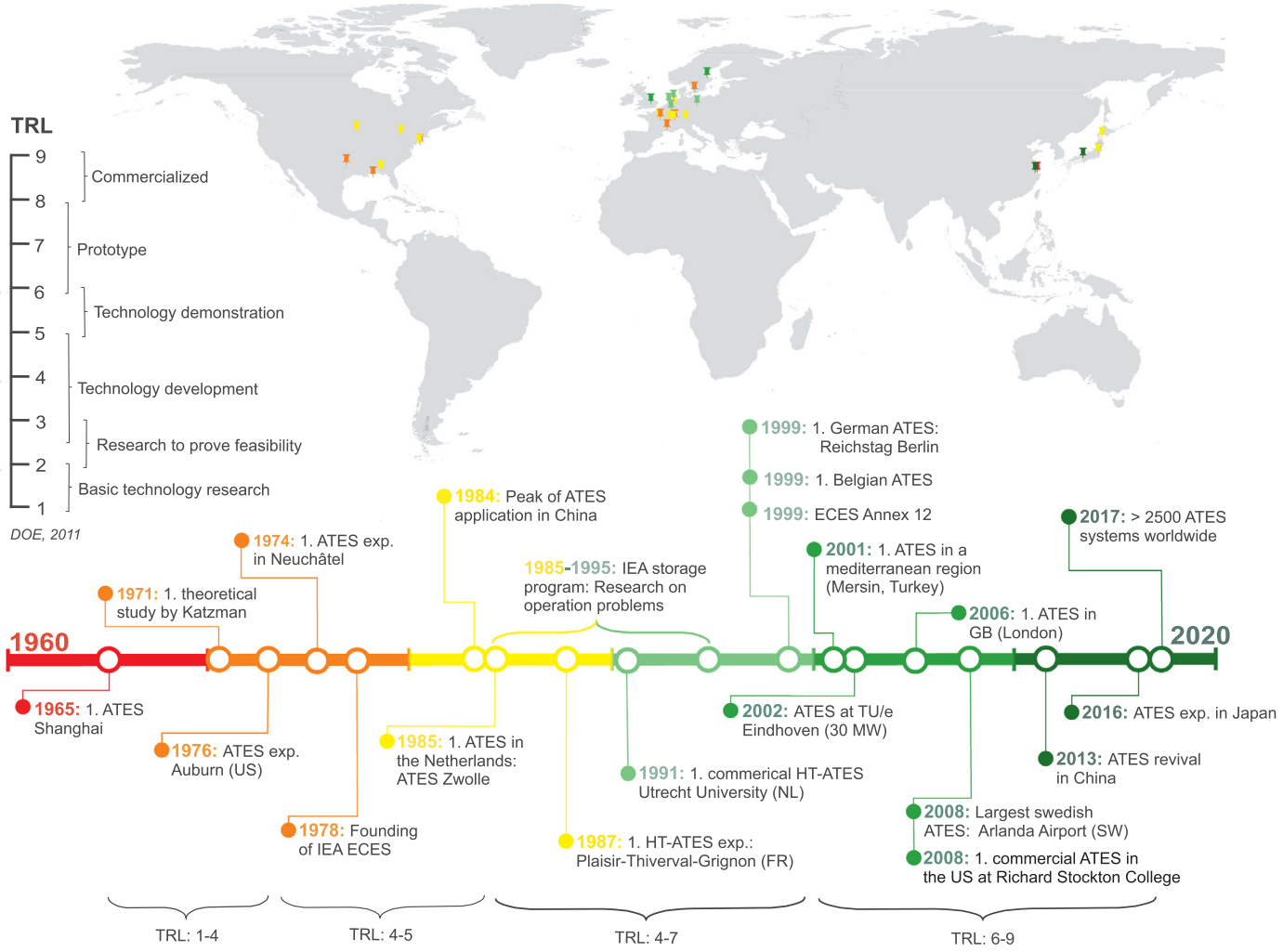
TRL
9 Commercialized
8
7 Prototype
6 Technology demonstration
5
4 Technology development
3 Research to prove feasibility
2 Basic technology research
1
DOE, 2011
1960
2020
1965: 1. ATES Shanghai
1971: 1. theoretical study by Katzman
1974: 1. ATES exp. in Neuchâtel
1976: ATES exp. Auburn (US)
1978: Founding of IEA ECES
1984: Peak of ATES application in China
1985: 1. ATES in the Netherlands: ATES Zwolle
1985-1995: IEA storage program: Research on operation problems
1987: 1. HT-ATES exp.: Plaisir-Thiverval-Grignon (FR)
1991: 1. commerical HT-ATES Utrecht University (NL)
1999: 1. German ATES: Reichstag Berlin
1999: 1. Belgian ATES
1999: ECES Annex 12
2001: 1. ATES in a mediterranean region (Mersin, Turkey)
2002: ATES at TU/e Eindhoven (30 MW)
2006: 1. ATES in GB (London)
2008: Largest swedish ATES: Arlanda Airport (SW)
2008: 1. commercial ATES in the US at Richard Stockton College
2013: ATES revival in China
2016: ATES exp. in Japan
2017: > 2500 ATES systems worldwide
TRL: 1-4
TRL: 4-5
TRL: 4-7
TRL: 6-9

Fig. 3. Chronology and milestones of global ATES development with the technical readiness level (TRL) according to DOE [27].

Table 2
Overview of early ATES test sites.

Country	Locations	Year	Temperature LT < 40 °C HT > 40 °C	TRL According to [27]	References
USA	Auburn University	1976	HT	2	[21,37–44]
	ST. Paul	1982	HT	3	[42,45–49]
	Tuscaloosa, Alabama	1982	LT	3	[50–57]
	Stony Brook	1982	LT/HT	3	[58,59]
	Melville	1985	LT	3	[60,61]
	Texas A&M University	1978	LT	3	[21]
Switzerland	Colombier	1974	HT	1	[17,33,34,62]
	Lusanne-Dorigny	1982	HT	2	[63]
France	Aulnay-Sous-bois	1983	LT	3	[64]
	Plaisir	1987	HT	3	[65–68]
	Trappes	–	HT	3	[59,69]
	Bonnaud	1976	LT	3	[31,32,62,69–74]
	Campuget	1977	LT	3	[17,59,73,75]
	Montreuil	–	LT	4	[59]
Canada	Scarborough	1985	HT	6	[76–81]
	Carleton University	1990	LT	7	[80,82]
Japan	Yamagata Yonezawa	1977	LT	3	[62] [21,62,83,84]
	Hokkaido. Sapporo	1982	HT	3	[19,21,64]
Sweden	Lomma	1991	LT	6	[25,85,86]
Germany	University of Stuttgart	1985	LT/HT	1	[87]
	Krefeld	1974	LT/HT	1	[88,89]
Netherlands	Groningen	–		4	[64]
	Bunnik	1985	LT	6	[68]
	Utrecht	1991	HT	6	[90,91]
Denmark	Horsholm	1982	HT	5	[59]

Table 3
Analytical and numerical studies analyzing storage efficiency and heat transfer processes of ATES (adapted from [145]). (+ considered; − not considered).

References	LT	HT	Groundwater flow	Buoyancy flow	Dispersion	Thermal interference	Aquifer heterogeneity	Building integration
[126,146–149]	+	−	+	−	+	−	−	−
[44,119,122,150–154]	−	+	−	+	−	−	−	−
[147,155–157]	+	−	−	−	+	−	+	−
[8,158–161]	+	−	−	−	−	+	+	−
[118,135]	+	+	+	+	−	−	−	−
[162–164]	+	−	−	+	+	−	+	−
[165–172]	+	−	−	−	−	+	−	−
[173,174]	+	−	+	−	−	+	−	−
[175]	−	+	−	−	+	−	−	−
[176]	−	+	−	+	+	+	−	−
[177]	+	+	+	−	−	−	−	+
[178]	+	−	−	−	−	−	−	+
[179]	−	+	−	−	−	−	−	+
[145,180,181]	+	−	−	−	−	−	−	+
[182–190]	−	+	−	−	−	−	−	−
[74,191]	−	+	+	−	+	−	−	−

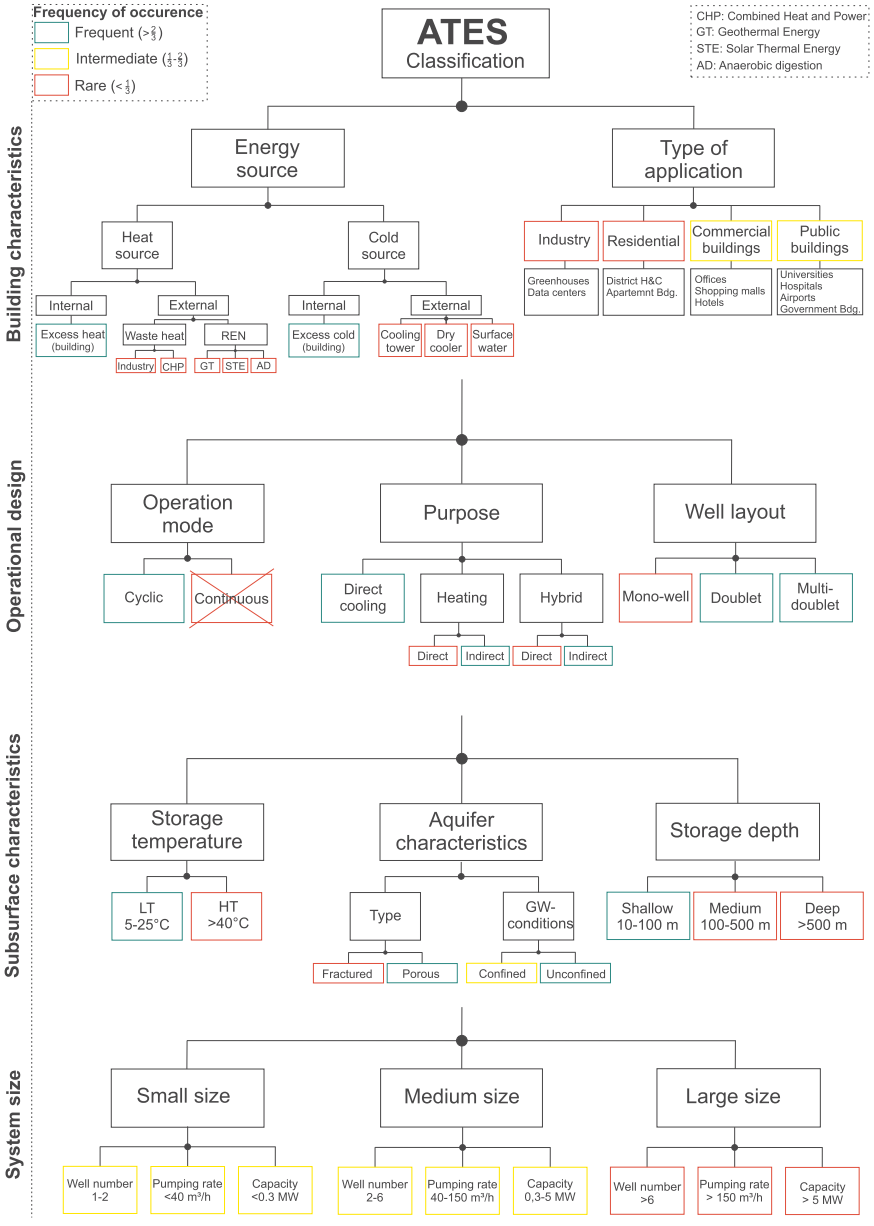

Fig. 4. ATES characterization in terms of building characteristics, operational design, subsurface characteristics, and system size.

Table 4
Summary of technical, energetic and financial parameters of worldwide ATES systems.

City (Country)	Purpose	Facility	Year	Well depth [m]	Well number	Maximum flow rate [m^3/h]	Capacity [MW]	Capital costs [Mio. €]	Payback time [years]	CO_2 savings [t/a]	Ref.
Amersfoort (NL)	H + C	IKEA Store	–	–	2	200	1.4	–	–	–	[204]
Utrecht* (NL)	HT	University	1991	260	2	100	2.6	1.1	5	750	[109,205]
Amersfoort (NL)	H + C	Office building	1996	240	2	–	2	1.0	6.5	–	[206]
Oslo (NW)	H + C	Airport	1998	45	18	200	7	2.65	2	–	[207–209]
Zwammerdam* (NL)	HT	Hospital	1998	150	2	20	0.6	1.3	–	–	[205]
Berlin (DE)	H + C	Reichstag	1999	60 / 300	12	100/300	–	–	–	–	[210,211]
Rostock (DE)	H	District heating	1999	20	2	15	–	1.02	–	–	[212,213]
Amsterdam (NL)	H + C	District heating	2000	130	4	500	8.3	–	6	–	[214]
Brasschaat (BE)	H + C	Hospital	2000	65	2	100	1.2	0.7	8.4	427	[215–217]
Malmö (SW)	H + C	Expo building	2001	75	10	120	1.3	0.35	1.5	–	[218,219]
Mersin (TR)	C	Supermarket	2001	100	2	–	–	–	–	–	[220]
Agassiz (CA)	H + C	Research Center	2002	60	5	40	0.563	0.22	6	–	[156]
Eindhoven (NL)	H + C	University	2002	28–80	36	3000	20	14.7	6–10	13,300	[142,221–223]
Malle ETAP (BE)	C	Office building	2003	67	2	90	0.6	0.34	7–15	23	[216]
Neubrandenburg (DE)	H	District heating	2005	1200	2	100	3.3	–	–	–	[224,225]
New Jersey (US)	C	University	2008	60	6	272	2	2.6	12	–	[107,223,226]
Arlanda (SW)	H + C	Airport	2009	20	11	720	10	5.0	5	7700	[227,228]
Copenhagen (DK)	H + C	Hotel	2009	–	2	–	2.4	–	6–7	366	[229]
Malmö (SW)	H + C	IKEA Store	2009	90	11	180	1.3	–	4.5	–	[230]
Copenhagen (DK)	H + C	Office building	2010	100	10	250	2.8	–	4	644	[231]
Greenwich (UK)	H + C	Museums quarter	2011	60	2	45	0.33	–	–	–	[232,233]
Shinshu (JP)	H + C	University	2011	50	5	–	–	–	–	–	[234,235]
London (UK)	H + C	Apartments	2013	70	8	400	2.9	–	–	–	[236]
Amsterdam (NL)	H + C	District heating	2015	–	7	1100	20	25.0	–	2900	[237]
Copenhagen (DK)	H + C	Airport	2015	110	10	–	5	8.0	8	1000	[238]

* No longer in operation.

design [59]. Nevertheless, since fewer problems were encountered in the years that followed, the interest moved from high temperature (HT) ATES (> 40 °C) to low temperature (LT) ATES (< 40 °C) in the following years [142,143].

After engineering feasibility had been demonstrated in various projects, LT-ATES was successfully established in the energy markets of the Netherlands and Sweden [25,86,144]. While early research mainly concentrated on solving technical, geochemical and engineering problems, the scientific focus in the year that followed shifted towards an optimization of ATES performance. Table 3 presents an overview of various studies, analyzing the impact of hydrogeological and thermodynamic parameters on the storage efficiency.

This ongoing research and optimization process is reflected in an increasing ATES attractiveness. Market incentive programs [57,86] and the open-mindedness of the (Dutch) authorities to support ATES [86,144] led to a growing number of projects, particularly in the Netherlands. This growth, however, is attributed to LT-ATES systems only. After early test sites and pilot projects faced significant problems [192], investors and planners lost confidence in HT-ATES systems [193]. To our knowledge, there are only 5 HT-ATES in operation worldwide, which means that 99% of all systems are represented by LT-ATES systems.

2.2. Technical development and application statistics

Each ATES project has to meet site-specific requirements, which are of geological, climatic, regulatory or building-specific nature. Consequently, a wide range of operational and technical specifications have been developed in the last decades. Such developments were summarized and discussed by several authors: in the early 1980s, Schaetzle et al. first published a pioneering in-depth summary of ATES designs and applications with focus on technical and economic aspects [194]. When ATES was successfully penetrating the energy market in Sweden and the Netherlands, Andersson [195] and Bakema et al. [196] reported on their experiences with ATES, concentrating more on application statistics and economic and environmental benefits. Furthermore, Lee [9,197], Nordell et al. [143], and Snijders and Drijver [198] presented a holistic description of operational principles, field investigations, aquifer characteristics, wellfield designs, and maintenance. Based on this previous work, the following sections summarize the technical developments of ATES, underpinned by practical examples.

The key requirement for ATES is the availability of an aquifer. The vast majority of ATES systems use unconsolidated aquifers as storage media. Deeper systems typically utilize sandstone or highly fractured rock [199]. The suitability of the subsurface depends on several hydrogeological characteristics such as aquifer thickness, hydraulic conductivity, or groundwater flow velocity. More detailed information on geological and hydrogeological requirements were described e.g, by Schaetzle et al. [194], Snijders and Drijver [198], Lee [9], or Sanner and Knoblich [200]. Fig. 4 characterizes ATES system designs in terms of operational, underground-related and technical aspects. The literature distinguishes between mono-directional and bi-directional systems [159,197]. This differentiation, however, is quite misleading, since mono-directional systems simply use the prevailing groundwater temperature by continuously pumping and reinjecting groundwater in one direction, like in geothermal doublets. Hence, only bi-directional systems can be referred to as ATES, as groundwater flow can be reversed to actively store cold and/or heat, respectively [10].

There are two different well designs (Fig. 1): multi-well systems use one or more well doublets to store thermal energy horizontally. In mono-well systems, heat and cold are separated vertically [201–203]. Mono-well systems show lower capital costs, since only one borehole has to be drilled. Thus, mono-well systems are mainly considered for HT-ATES systems with high drilling depths, or small-scale systems with low injection and production rates. The disadvantage of mono-well systems is the high susceptibility to thermal interference, hence thick aquifers are required. Depending on regional climatic conditions and specific building requirements, ATES is applied to direct cooling, direct or indirect heating and hybrid systems [9,26,195]. Indirect systems are required if the outlet temperature of the ATES does not meet the inlet temperature demand of the heating system. To charge an ATES with thermal energy, different kinds of heat and cold sources are considered, such as waste heat from cogeneration, renewable energies or dry cooler

(Fig. 4). However, the standard case is to re-use the seasonal heat and cold of the building. To illustrate the wide range of specifications, Table 4 summarizes the technical and economic parameters of 25 worldwide ATES systems.

The capacity of an ATES system ranges between 0.1 and 0.3 MW for small-scale and between 5 and 30 MW for large-scale systems. While the well number and the pumping rate are approximately proportional to the heating and cooling capacity, several projects indicate a decline in specific capital costs (€/kW) with increasing system size. This is because larger systems can be designed more efficiently than smaller ones [26,195,222]. Direct cooling systems achieve storage efficiencies of up to 90%, indirect systems reach 40–85% [7,160,170,180,185,199]. Typical payback times compared to conventional systems range from 2 to 10 years [61,86,195,217,239–243]. ATES for cooling show lower payback times, since the stored cold can be used directly without a heat pump [25,222]. The lifetime of an ATES system is estimated at 25 years by Hartog et al. [244] and at 30–50 years by Bloemendal et al. [203].

The investigation of 74 ATES systems in the Netherlands has revealed an average CO_2 saving of 0.46 kg per m^3 of pumped groundwater [245,246]. This corresponds to an estimated annual reduction in CO_2 emissions of 150 t/a for a small-scale system and of up to 1500 t/a for a large-scale system. By comparison, the average CO_2 savings for a ground-source heat pump (GSHP) unit ranges between 1.8 and 4.0 t/a, depending on the replaced heating system and used electricity mix [247]. The largest ATES worldwide at the campus of the University of Technology in Eindhoven (NL) saves more than 13,000 t of CO_2 per year [223]. This is equivalent to the average annual CO_2 footprint of 800 American or 1300 German citizens.

In the Netherlands, about 70% of all ATES systems supply energy for public and commercial buildings (e.g. offices, shopping malls, hospitals, hotels). The remaining 30% are installed in industrial or residential buildings [143,248]. Similar proportions are reported from Sweden [241] and Denmark [249]. Recently, ATES has been increasingly considered to reduce the high energy costs of greenhouses and data centers [148,193,250–253].

3. Worldwide ATES spatial distribution

The establishment of renewables in the energy market is often impeded by several market barriers (Section 4). Even though the economic and technical viabilities have been successfully demonstrated, only a small proportion of the potential of ATES technology has been tapped yet. Statistics on the global application of ATES are indispensable for identifying such country-specific market barriers. Despite this great significance, the literature lacks such statistics. So far, only Lee [9] discussed the status of ATES in all relevant countries. However, the figures compiled are neither up-to-date nor complete. Beyond that, several authors summarized their experiences with ATES in several country updates [15,26,80,142,209,213,239,241,254–264]. These country updates are analyzed to provide a global overview of ATES applications. In cases where data from the literature were not sufficient, further inquiries for additional information were sent to ATES experts. The latter was done for ATES systems in China, Denmark, Sweden, Turkey, and the US.

To our knowledge, more than 2800 ATES projects have been successfully implemented worldwide. The total amount of heat and cold produced by all ATES systems is estimated at more than 2.5 TWh per year, which equals the average thermal energy consumption of 150,000 households in Central Europe. However, this success story is contributed by only a few countries: around 85% of all systems are installed in the Netherlands (2500); a further 10% are found in Sweden (220), Belgium (30), and Denmark (55). Fig. 5 illustrates the global application statistics and global spatial distribution of ATES. Comparison of Figs. 5 and 3 indicates that countries that were active in research in the 1970s and 1980s have now lost their interest in ATES. This is especially the case for Switzerland (0), France (0), the US (2), and Canada (4).

Regardless of the great discrepancy in ATES application worldwide, the number of ATES systems is expected to increase further. Significant growth rates are reported from the Netherlands, Sweden, Denmark, and Belgium [254,265]. Furthermore, progressively more countries show an interest in ATES technology. After the first ATES system was realized in Great Britain in 2006 [266], almost a dozen projects were implemented in the course of the last decade. As many large UK cities have subsurface conditions suitable for ATES, further projects are expected [267]. In Germany, ATES was considered first in the early 1980s as a consequence of the oil crisis and in order to provide an alternative to expensive cooling methods for nuclear power plants [89]. Currently, there are, however, only four operating ATES systems for heating and/or cooling purposes. Consolidated findings were gained from these projects [178,186,187,210,211,213,224,225,268–277]. In Germany, there has been an increasing interest in storage technologies again recently. Hence, 4 ATES projects are in the planning or construction phases:

- An ATES for the new campus building of the Leuphana University in Lüneburg [277–279]
- The collaborative project called “Geospeicher.bw” aims for the implementation of three ATES systems in the federal state of Baden-Württemberg.
- The BMW Group, supported by TU Munich, designs a HT-ATES for storing temperatures of up to 130 °C with an injection rate of 280 m^3/h in a Jurassic limestone aquifer at a depth of about 500 m [280].
- The city of Hamburg strives to store waste heat from an incineration and a sewage plant with the long-term aim to supply heating for 8000 households. Feasibility of the project was successfully demonstrated by a pilot ATES with one well doublet. The pilot plant is expected to be up-scaled in the near future.

In China, ATES is experiencing the beginning of a revival. After early projects had to be shut down due to technical problems, 6 ATES systems have been successfully implemented since 2013. ATES provides heat and cold for a poultry farm, for two public buildings, and three greenhouses [24]. In Japan, two demonstration plants were successfully realized, and further projects are expected [281]. Although there are currently no further plans for ATES in Turkey [282], an ATES for the cooling of a supermarket and several feasibility studies have proven the economic and technical feasibility of ATES in Mediterranean regions [220,251,283,284]. A team of experts from universities, authorities, and the industry is trying to evaluate potential barriers to the penetration of the Turkish energy market [282].

4. Market barriers

The country-by-country statistics presented in the previous section raise the question for the reasons for the great discrepancies in ATES development worldwide. In the most industrial countries, expect for in Sweden or the Netherlands, ATES has not been in the focus yet. This reveals a trend that does not reflect the high suitability for ATES [285] and is opposite to the great demand for sustainable heating and cooling in these countries. Thus, the development of ATES application is not only influenced by subsurface and climate conditions, but also by several market barriers, which are of socio-economic, regulatory, technical and political natures (Sections 4.1, 4.2 and 4.3) [286]. However, the kind of market barrier influencing technology development is subject to a dynamic process. Hence, the country-specific market development has to be considered when identifying potential market barriers on a global level. Van Mourik first analyzed market barriers for ATES development [144]. He concentrated on cooling systems in the Netherlands. Within the framework of the project “e-use”, Bloemendal et al. conducted a questionnaire in order to assess market barriers for ATES in the Netherlands, Belgium, Germany, Italy, and Spain [287]. More generally, Dinçer and Rosen analyzed hurdles to be overcome for TES systems

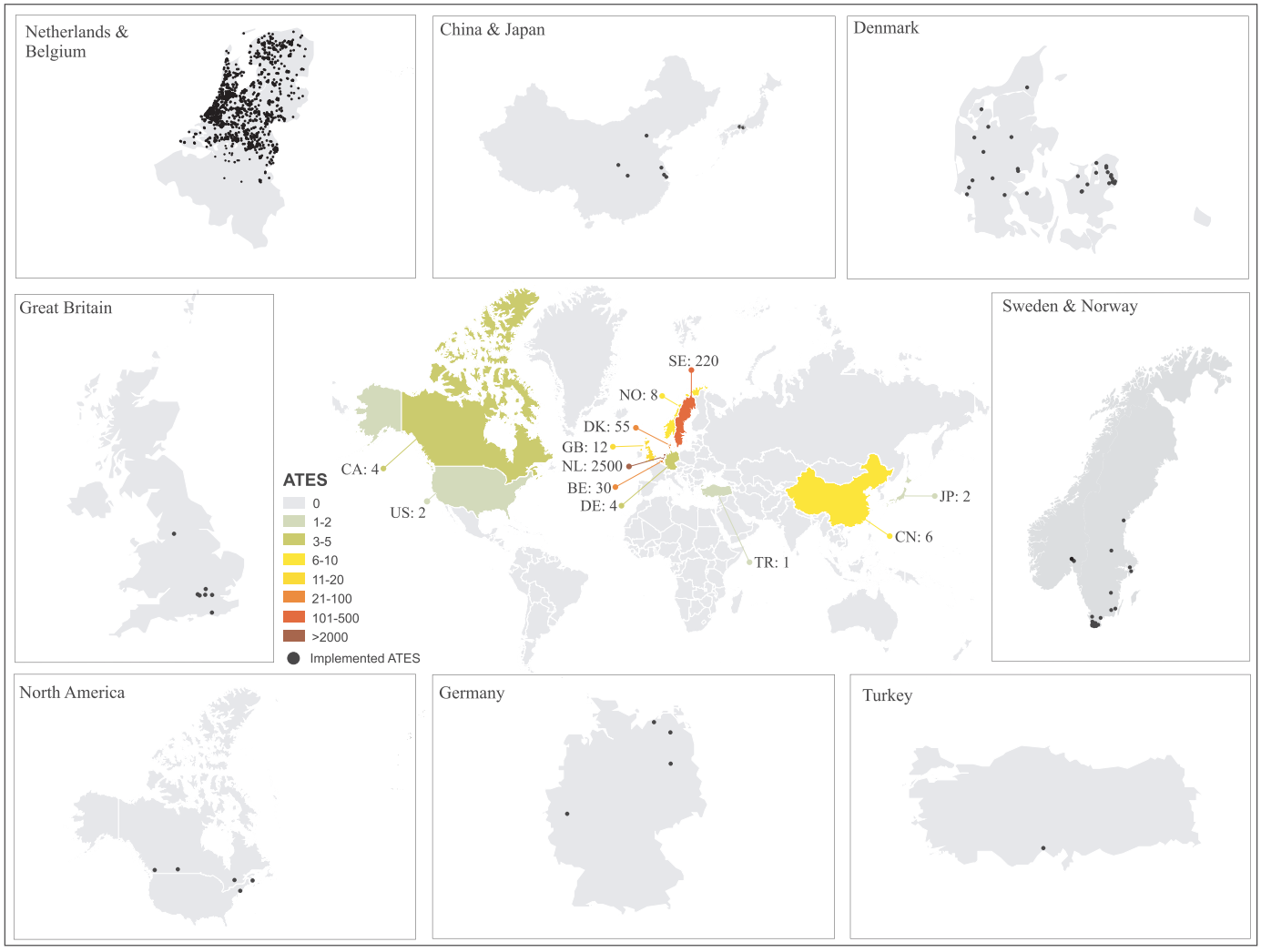

Fig. 5. Global spatial distribution of ATES.

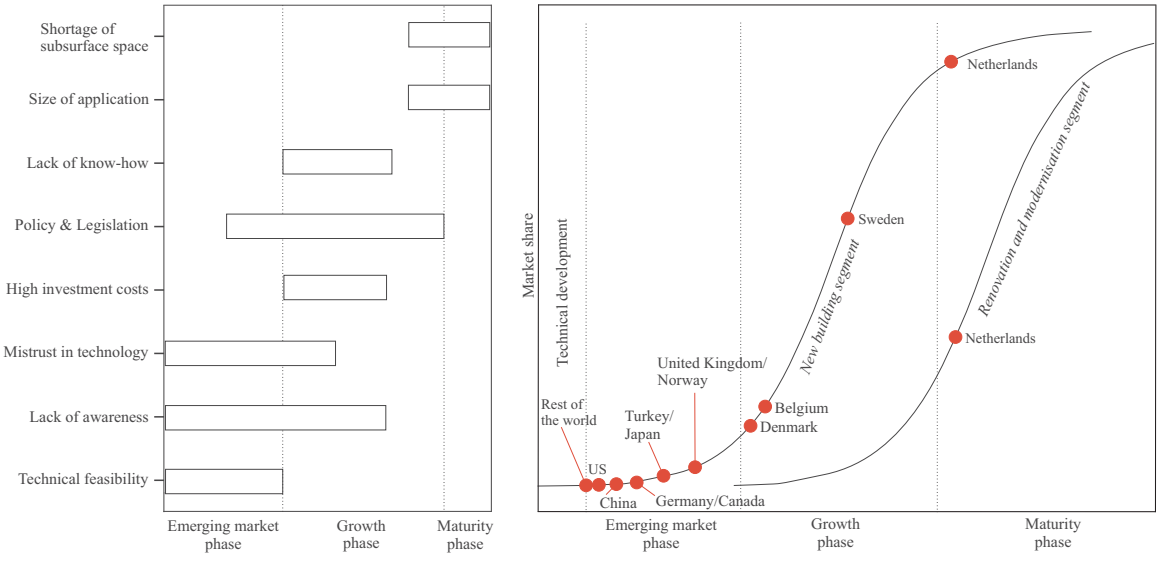

Fig. 6. Left: market barriers limiting ATES development as a function of the market development level. Please note that suitable subsurface and climatic conditions are assumed. Right: market development of ATES in all relevant countries considering new building and renovation segments.

[11], and Monti et al. studied obstacles to geothermal projects [288]. Based on these previous works, Fig. 6 illustrates market barriers for ATES commercialization as a function of the market development level.

The following section analyses potential barriers (1) from the perspective of an emerging market phase, (2) from the perspective of a growth phase, and (3) from the perspective of a maturity phase.

4.1. Market barriers in the emerging market phase

More than 2800 ATES systems have been successfully implemented worldwide. According to Andersson and Sellberg, there are no unsolved technical problems if the storage temperature is restricted to less than 40 °C [25]. Although feasibility was demonstrated and benefits are significant, ATES, in most countries, has not yet penetrated the energy market. Thus, until entering the stage of commercialization, the dominating hurdle is less a matter of technical feasibility than a lack of awareness of the technology [81,287]. However, this is not the case for HT-ATES, where serious technical problems, such as scaling or corrosion of wells, have to be solved first.

In most countries, politicians, stakeholders, and HVAC (heating, ventilation, and air conditioning) installers often do not consider ATES and, therefore, this technology is not part of the new energy design. The most promising way to promote a new technology in the population is the successful realization of demonstration projects [138,289]. Such projects not only draw public attention but also prove technical and often economic feasibility. The term “demonstration project”, however, implies that it is not sufficient to just take care of the technical installations. It is also essential to propagate the environmental and economic benefits of the technology. The Reichstag building in Berlin with over 3 million visitors per year serves as a good example: an ATES has been providing heating and cooling for more than 15 years. Even though the energy system of the Reichstag has been the first of its kind in Germany, there is no information panel providing background data about the technology. Probably only a small proportion of the visitors and members of parliament (MP) realizes, how the German parliament is actually heated and cooled. As awareness of the technology increases, any renewable initially is facing prejudices and mistrust [290]. Hence, it is of utmost importance that the success of the first projects installed in a country is guaranteed. However, this means that contractors have to invest in the project to guarantee its success and clients have to accept difficulties in the start-up phase [291].

Another great hurdle for early ATES projects is the high initial investment compared to conventional systems. High capital costs, especially for the drillings, make ATES appear unattractive at first glance. While financial evaluations are rare in the field of ATES research, decision-makers are often not aware of the typical low payback times of such systems [292]. Another issue is the question of who is taking the exploration and investment risks. Test drillings are often indispensable in order to explore the essential subsurface suitability for ATES (i.e., technical feasibility). However, there is no guarantee for the success of a test drilling, which means some uncertainty and poses a specific risk to the client.

4.2. Market barriers in the growth phase

Entering the commercialization stage, the type of potential barrier shifts from socio-economic to more regulatory issues. Since experiences gained with ATES are rare in most countries, numerous legal questions have to be addressed, discussed, and finalized in regulations or even laws [293]. This applies especially to the permitted injection temperature, the minimum distance to other geothermal applications, the maximum drilling depth, and the distance to contaminated sites. Environmental risks of shallow geothermal energy can be subdivided into hydrogeological, thermal, chemical, and microbiological impacts [294]. Potential impacts of ATES on groundwater quality were investigated by several field monitoring campaigns [244]. For temperature levels of below 30 °C, groundwater quality is predominantly affected by mixing of stratified groundwater and less by temperature effects [244]. However, according to Bonte, an early identification of interferences and synergies between different subsurface activities can avoid negative interference of ATES with other subsurface functions [294]. At present, there are significant differences in the legal framework both at international [295–297] and even national levels [295,297]. Experience gained in the Netherlands have illustrated that courage of the authorities to create a proper legislative framework is indispensable for enabling technology growth in a country [260]. Authorities have to strike the right balance between the protection of groundwater and an acceptable limitation of a promising technology. In Sweden, for instance, the permit procedure averages 12 months [256]. After introduction of a new legislative framework in the Netherlands in 2014, the permit procedure was shortened from 12 to 2 months for normal,- low-risk projects. Only in the case of high-risk projects (complex hydrogeological settings), it may take up to 6 months. Hence, top priority should be placed on a standardized, transparent and coherent legal framework. To support authorities in establishing appropriate, scientific-based guidelines, negative effects of ATES on groundwater quality or neighboring underground users have to be assessed. In recent years, much research was undertaken to identify negative effects on groundwater quality [294,295,298–306], changes in groundwater chemistry [244,307–319], and potential impacts on microbiology [311,320–324]. In order to facilitate a scientific-based permit procedure, the knowledge gained has to be bundled and expressed in the form of specific guidelines for authorities, planners, and industry. First steps in this direction were recently made in the Netherlands with the collaborative research program “Meer met Bodemenergie” (“more with subsurface energy”). Within this framework, all relevant actors were involved in determining the long-term influence of geothermal energy on the subsurface. The main recommendations to the authorities were to limit the maximum injection temperature to 25 °C and to intensify underground management [287]. In this context, there has been also a growing interest in the combination of enhanced groundwater remediation and ATES [309,325–335].

Another obstacle in the early commercialization phase is the lack of knowledge among national and local consultancies. This was observed with pilot projects in the Netherlands at the end of the 1980s [144]. Large consultancies often do not want to harm their reputation by an unknown new technology, and small consultancies often do not have the capabilities to manage large and new projects [144]. As rich experiences have been gained with ATES in several countries, initiation of a cross-national knowledge transfer is important to guarantee the success of early projects [144,291].

4.3. Market barriers in the maturity phase

With a successful establishment in the energy market and a steadily increasing number of implemented systems, a scarcity of subsurface space can also be a limiting factor. In many Dutch cities, the increasing demand for ATES exceeds subsurface space. Permits for new shallow geothermal energy systems are currently given on a “first-come-first-pump” basis [203]. Hence, there is an increasing demand for a cross-sectoral subsurface management [8,287,295,336–340]. Growing concerns about this issue are, however, not only limited to the Netherlands. In Germany, 12% of the underground excludes the use of geothermal technologies [287]. This area does not include potential horizons for Carbon Capture and Storage (CCS) technology, nuclear waste repositories, and over 15,000 contaminated sites. Additionally, in Germany, there are already more than 350,000 GSHP systems in operation [341]. These figures illustrate that underground space is already highly limited even without ATES activity. To be able to facilitate a sustainable permit procedure, other countries could and should learn from the lessons learned in the Netherlands and apply an underground management system from the early beginning.

Early ATES pilot projects usually focus on new buildings, where the energy system can be adjusted to ATES-specific requirements. Nevertheless, there is also a great demand for a sustainable heating and cooling for the old building stock. In the very early days of ATES application in the Netherlands, nearly 90% of ATES projects had to be cancelled due to an insufficient building integration [145]. The main problem of integrating ATES in an old building is to replace the existing HVAC installations, which would drastically exceed the budget of an ATES project. In residential areas, ATES often has to compete with oil or gas boilers. As the old system has been proving its functionality for decades, it is difficult to convince homeowners of investing in a new heating and cooling system. Another hurdle is the size of residential buildings: due to the smaller system capacity, financial savings are significantly lower compared to those through ATES for large buildings. To enhance the ability of ATES to compete with other storage techniques in the residential sector, it will be crucial to match the high energy supply of ATES to the low energy demand of the small building stock. The combination of district heating or cooling with ATES, however, is a promising solution [179,256,342] but requires a regional or urban energy management.

5. Conclusions

With more than 2800 systems in operation worldwide, ATES technology has proven its ability to efficiently tackle the seasonal mismatch between periods of highest energy supply and highest energy demand. Nevertheless, this success story is almost entirely limited to a few north-western European countries. Despite the high potential in most developed economies, ATES still has difficulties in capturing significant positions in relevant energy markets. To benefit from the growing interest in TES technologies, political and institutional actors are obliged to create a suitable framework for ATES development, which includes an appropriate legislative basis and well-placed financial subsidies. Based on the reviewed literature, the following research gaps have to be carefully addressed by future research and public activities:

Economic evaluation

The literature is comprehensively reviewed in this work, but profound economic considerations are quite rare in the field of ATES. Even though several authors have summarized payback times and capital costs from several projects, only Ghaebi et al. have carried out a comprehensive economic analysis [343]. This is remarkable, as many authors have identified the lack of awareness of financial benefits as a key barrier to market penetration. Future studies should therefore collect and analyze financial parameters of existing projects in order to evaluate the economic competitiveness of ATES compared to both conventional energy systems and other TES solutions. The identification of parameters, which affect the economic performance of an ATES, would not only be a first step towards a financial optimization of ATES plants, but also a tremendous support for stakeholders and decision makers to estimate capital costs and financial payback times.

Further research into HT-ATES

The total amount of solar radiation reaching the roof of a typical building is more than its annual heating demand. The storage of solar thermal energy (STE) is becoming increasingly important [185]. Different storage solutions are considered for STE storage in practice [344,345]. ATES has attracted very little attention in this field, as storage temperatures of STE can be up to 95 °C [346]. In order to build up confidence in HT-ATES, more attention has to be paid to crucial hydrogeochemical-related problems such as corrosion or scaling of wells and heat exchangers.

Building integration

The vast majority of modeling studies focuses on heat transfer processes in the subsurface. However, experiences from existing projects identified the connection of subsurface and energy system to be the main bottleneck. The dynamic change in heating and cooling demand of a building is often neglected, which is reflected by a mismatch between simulation results and reality [347]. Additionally, HVAC designs are often based upon conservative assumptions, resulting in oversized ATES systems. The development of smart energy concepts and design models would therefore support optimizing the dimensioning of ATES systems.

Potential studies

Several authors have analyzed the potential of ATES on a local [350], regional [348,349] or global scale [285]. However, these studies only allow a first estimation of ATES potential, since important factors were not considered. Even though Bloemendal et al. indicated that ATES suitability is high in almost all developed economies, there is an urgent need for quantification of the ATES potential [285,351]. As potential maps serve as a useful tool to stimulate the decision-making process of new energy concepts, future investigations should also take local characteristics into account. This especially relates to geographical, regulatory, hydrogeological and climatic factors.

- **Geological & hydrogeological parameters** (potential storage horizons, groundwater flow, aquifer thickness, groundwater temperature, fluid chemistry, oxygen concentration);
- **Geographical parameters** (thermal energy sources, thermal energy demand, existing infrastructure, potential conflicts with other subsurface users);
- **Regulatory parameters** (groundwater protection areas, maximum drilling depth, maximum distance to geothermal systems);
- **Climatic parameters** (temperature, solar radiation, heating and cooling degree days).

Almost 3000 ATES systems are in operation worldwide demonstrating the large potential of ATES to significantly reduce GHG emissions of the thermal energy sector. Several market barriers still impede ATES market entrance in most economies. Nevertheless, decarbonization of the heating and cooling sector is indispensable to achieve COP21 targets. Thus, further research and development (R&D) activities are required to promote ATES development beyond north-western Europe.

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Conflicts of interest

None.

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